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A POST-ACCELERATOR FOR THE U.S. RARE ISOTOPE ACCELERATOR FACILITY*

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Abstract

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The proposed Rare Isotope Accelerator (RIA) Facility includes a post-accelerator for rare isotopes (RIB linac) which must produce high-quality beams of radioactive ions over the full mass range, including uranium, at energies above the coulomb barrier, and have high transmission and efficiency. The latter requires the RIB linac to accept at injection ions in the 1+ charge state. A concept for such a post accelerator suitable for ions up to mass 132 has been previously described [1]. This paper presents a modified concept which extends the mass range to uranium. A high resolution separator for purifying beams at the isobaric level precedes the RIB linac. The mass filtering process will provide high purity beams while preserving transmission. For most cases a resolution of about m/Δm=20,000 is adequate at mass A=100 to obtain a separation between isobars of mass excess difference of 5 MeV. The design for a device capable of purifying beams at the isobaric level included calculations up to 5th order.

The RIB linac will utilize existing superconducting heavy-ion linac technology for all but a small portion of the accelerator system. The exceptional piece, a very-low-charge-state injector,

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section needed for just the first few MV of the RIB accelerator, consists of a pre-buncher followed by several sections of cw, normally-conducting RFQ. Two stages of charge stripping are provided: helium gas stripping at energies of a few keV/u, and additional foil stripping at ~680 keV/u for the heavier ions. In extending the mass range to uranium, however, for best efficiency the helium gas stripping must be performed at different energies for different mass ions. We present numerical simulations of the beam dynamics of a design for the complete RIB linac which provides for several stripping options and uses cost-effective solenoid focusing elements in the drift-tube linac.

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1. ISOBAR SEPARATOR

The block-diagram of the rare-isotope-beam (RIB) linac is shown in Fig. 1. The first section consists of a high-resolving power mass separator system in which the beam enters and exits at 100 keV in DC mode. We assume that at the entrance the beam has a transverse emittance of 10 π·mm·mrad in both the vertical and horizontal planes; however, the spatial width of the beam must be 1 mm in the horizontal and 8 mm in the vertical plane. This ensures a large span along the horizontal plane when the beam is inside the dipoles and almost parallel focusing along the vertical plane throughout the linac.

A diagram illustrating the layout and resolution of the spectrometer is shown in Fig. 2. There are two magnetic bending sections that consist of mirror-symmetric dipoles and each section is at a different potential. The first bend is at ground potential and is called Section H (between points A and C), since the beam is at the higher energy (100 keV). The mass of interest bends

60º at each dipole at a 2.5 m radius. A multipole magnet set between the two dipoles corrects for the geometric aberrations in the optical system up to 5-th order. A Monte Carlo simulation of the expected mass spectrum at point C is shown in the inset plot (a), where the mass difference ratio is $\Delta m/m=1/20000$, assuming that there is no energy spread in the beam and that the phase space distributions are Gaussian. For a ±10 eV Gaussian spread in energy the resolution deteriorates as it is shown in plot (b). To eliminate this effect another bend has been applied, after having decelerated the beam from 100 to 10 keV, by two immersion lenses at Section I (between points C and D). The lower energy bend at Section L (between points D and F) is almost identical to Section H; however, it is scaled down by a factor of $\sqrt{10}$ and floats at 90 kV to cancel the energy dispersion imposed by Section H. After accelerating the beam back up to 100 keV at the section between points F and G, we obtain the spectrum shown in plot (c), where there is a 5% contamination at the central peak from the adjacent ones. The method of calculation and details of the optics of this scheme have been detailed by Portillo and others elsewhere [2].

2. *LINAC DESIGN CONCEPT*

The RIB accelerator system must: 1) Efficiently accept and accelerate ions over the full mass range, including uranium; 2) Provide an output beam at any energy up to 5-10 MeV/nucleon; 3) Maintain a longitudinal emittance of $0.5\ \pi\cdot$keV/u·nsec over the full range of energy and mass. The ability of the linac to maintain a small longitudinal emittance (i.e. good time and energy resolution) will be critical in enabling experiments to use time-of-flight techniques while simultaneously having available good energy resolution and adequate beam intensity.

The technology developed for existing superconducting heavy-ion linacs, characterized by excellent performance and a very high degree of modularity, provides a basis for all but a small portion of such a RIB accelerator system. The exceptional piece is a very low charge state injector section. The most efficient generation of beams of rare isotopes requires singly charged ions at initial injection. Very-low-charge-state ions can most efficiently be bunched and accelerated by using several sections of cw, normally-conducting RFQ for the first few MV of the RIB accelerator.

For best efficiency over the full mass range, helium gas stripping must be performed at different energies for different mass ions. The linac following this stripping can accelerate ions of charge to mass ratio 1/66 and above. By stripping at 7 keV/u some 55% of an incident ^{132}Sn beam, for example, can be stripped into charge state 2+ and further accelerated [3]. For the heavier ions of Z>54, higher charge states are required, for which the best stripping efficiency is achieved at the higher energy of 20 keV/u.

The RIB linac consists of the following main sections (see Fig. 1 and Table 1) [4]:

- An injector with three sections of normally-conducting RFQs.
- A superconducting linac which will accelerate ions of q/m > 1/66 to 680 keV/u or more.
- A carbon-foil stripper at beam kinetic energy per nucleon W_n>680 keV/u, when necessary, to provide a q/m>2/15 for the last stage of acceleration. The beam energy at this point depends on the particular charge-to-mass ratio.
- A superconducting linac to accelerate ions of q/m > 2/15 to energies of 6 MeV/u or higher.

3 NORMAL-CONDUCTING RFQ INJECTOR SECTIONS

The buncher, the first two sections of 12 MHz RFQ, and both He gas-stripper cells will be placed on a 380 kV open-air variable-voltage platform. Placing these elements on a variable-voltage platform allows operation with a fixed constant velocity profile for the full mass range of ions, including uranium. The output of the first section is at 7 keV/u, and the beams of 66 <

mass < 133 will be charge-stripped at this point. Whether stripped or not, ions of any mass and charge state, including mass 240 at charge state 1+, will be further accelerated by the next section of the 12 MHz RFQ to an energy of 20.3 keV/u. At this point the beams of mass > 132 will be stripped. The RFQ operating at 24.25 MHz will accelerate the ions, now at a charge state q/m > 1/66, to an energy of 62.6 keV/u for injection into the superconducting linac.

The 12 MHz four-harmonic bunching system which is presently in use on the ATLAS accelerator operating at Argonne National Laboratory (ANL) may be most suitable for this application. The RFQ should operate at as low a frequency as is practicable to maximize the transverse focusing strength. As it has been demonstrated at ANL the split-coaxial RFQ geometry is appropriate for operation at 12 MHz [5]. The RFQ is designed for a minimum charge-to-mass ratio of 1/240. Ions of higher charge state are accommodated by simply scaling both the platform voltage and the RFQ rf voltage to match. The proposed cw inter-vane voltage of 92 kV with a mean bore radius of 9 mm has been proven entirely practical in extensive tests of the prototype 12 MHz RFQ at ANL. The last two sections of the RFQ will be based on a more effective accelerating structure, a hybrid RFQ [6]. We found that the concept of separated accelerating and focusing zones can be applied to the acceleration of heavy ions with q/m≥1/240 and at very low energies if the beam focusing is provided by rf quadrupoles. The DTL accelerating and rf focusing sections can be integrated into a single resonant structure we call the hybrid RFQ. The 12 MHz H-RFQ will be based on the resonant structure shown in Fig. 3. A 1:2 aluminum cold model of the 12 MHz H-RFQ was designed. Fabrication and assembly of the cold model was completed and the structure is being studied for electrodynamic properties. Fig. 4 shows a segment of the H-RFQ containing rf quadrupoles and drift tubes.

Numerical simulations of the beam dynamics through the entire chain of RFQ sections have been performed. The proposed design achieves longitudinal emittance as low as 0.2 π·keV/u·nsec for 80% of the DC beam entering the buncher. Several rf bunchers are required for matching between the sections of RFQ. Transverse focusing in the transitions can be done with either electrostatic quadrupoles or SC solenoids.

Light ions will exit the HV platform above the input matched velocity of the following ground-potential H-RFQ. To achieve velocity matching for these ions, a rf cavity with effective voltage ~60 kV is required. Such a voltage can easily be produced, for example, by a normally-conducting folded-quarter-wave resonator with ~1 kW rf power.

4 SUPERCONDUCTING LINAC (BETWEEN THE STRIPPERS)

The low-charge-state injector linac can be based on established interdigital drift-tube SC niobium cavity designs, which can provide typically 1 MV of accelerating potential per cavity in this velocity range [1]. The low-charge-state beams, however, require stronger transverse focusing than it is used in existing SC ion linacs. For the charge states considered here ($q/m = 1/66$) the proper focusing can be reached with the help of strong SC solenoid lenses with fields up to 15 T. Commercial vendors now offer a wide range of high field magnets in the range of 10 to 17 Tesla [7]. Since the solenoids will operate at appreciably higher fields than in the present-day ATLAS linac, in order to protect the superconducting cavities from the solenoid magnetic fields more magnetic shielding will probably be required. We have allowed for this requirement by assuming the focusing periods to be relatively long.

The SRF linac consists of 54 interdigital cavities operating at -20° synchronous phase (see Table 1), and each cavity is followed by a SC solenoid. This linac can accelerate any beam with $q/m \geq 1/66$ over the velocity range $0.0011 \leq \beta \leq 0.04$. With the advent of high helium-stripping efficiency adequate radioactive beams intensities will be delivered to the astrophysics experiments [3]. The helium stripping efficiency for masses 240≥m≥66 is in the range 30%-45% while masses m≤66 do not require any stripping. It allows to obtain beam intensities higher by a factor of ~25 as compared with RIB accelerators based on the ECR charge breeder.

5 POST-STRIPPER SUPERCONDUCTING LINAC

After the second stripper, the desired charge state must be selected and further accelerated to the beam velocity required to match to the ATLAS linac section in order to provide the last stage of acceleration to the desired beam energy. Fig. 5 shows the average charge state as a function of the atomic number of the ion beam. The calculations were made taking into account the beam kinetic energy at the location of the second stripper.

The post-stripper section of the RIB linac will be designed for the acceleration of multiple charge state beams to enhance the available beam intensities for experiments. As was shown in [8] a wide range of the charge spread Δq/q, about 20%, can be accepted and accelerated in the ATLAS accelerator. We have restricted the possible range of Δq/q to ≤ 11% in order to avoid emittance halo in phase space. Fig. 5 presents a possible range of charge states Δq acceptable for the following acceleration. As a consequence of multiple charge state acceleration the total stripping efficiency is significantly higher than for the single charge-state beams as seen from Fig. 6. However, the transverse and longitudinal emittances of multi-q beams will be larger by a factor of ~3 as it follows from beam measurements in ATLAS [8].

Further acceleration by eight SRF cavities of β_G =0.037 is required in order to bring the beam energy to approximately 1.4 MeV/u and match the velocity acceptance of the β_G=0.06 resonators in ATLAS. The new, low-velocity portion of the Rare Isotope Beam linac matches into the existing ATLAS linac at the start of the split-ring resonator section of ATLAS. The ATLAS linac consists of 12 'low-beta' (β_G =0.06) resonators and 30 'high-beta' (β_G =0.105) resonators of the 'split-ring' class. An existing 'spare' cryostat will be outfitted with eight quarter-wave resonators recently designed for β_G =0.15 and installed at the end of ATLAS. With this addition, 38 high-beta resonators will be available and the voltage of the present ATLAS configuration will be enhanced. The existing 12-MV Positive Ion Injector (PII) linac of ATLAS is not planned to be used as part of the RIB linac. The PII section of the present ATLAS linac may still be used for certain experiments requiring stable beam acceleration as part of the total experiment and is also available as an alternative acceleration scheme for rare isotopes if the ECR charge breeder approach is incorporated into the facility at a later date.

6 CONCLUSION

The RIB linac for the RIA facility is mainly based on low velocity SRF cavities and the existing ATLAS linac. Initial acceleration up to 62 keV/u is provided by room temperature RFQ structures. This section of the linac accepts singly-charged ions with mass number up to 240. The use of a gas stripper at 7 keV/u or 20 keV/u provides high stripping efficiency and generates beams with charge-to-mass ratio 1/66 for further acceleration. Multiple charge state beam acceleration after the second stripper will be used to increase the intensities of heavy ion radioactive beams.

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FIGURE LEGENDS

Figure 1. Block-diagram of the RIB Linac.

Figure 2. Layout of dual-potential spectrometer. The spectrometer can be broken up into 4 sections as described in the text. The inset shows a plot of the beam distribution at points C and F.

1 – Isobar separator, 2 – High voltage platform, 3 - 12 MHz RFQ, 4 – 12 MHz Hybrid RFQ, 5 – helium strippers, 6 - 24 MHz Hybrid RFQ, 7 – SC Linac between the strippers, 8 – carbon stripper, 9 – beams to astrophysics experiments, 10 – SC booster linac, 11 – ATLAS, 12 – high energy beams.

Figure 3. Side view of 1:2 cold model of the 12 MHz hybrid RFQ.

Figure 4. Photograph of the H-RFQ segment containing rf quadrupoles and drift tubes.

Figure 5. Charge states of heavy ions as a function of atomic number after the passage of the carbon stripper. The solid curve shows charge state of the highest intensity. The dots show the range of charge states accepted for the further acceleration.

Figure 6. RIB linac overall stripping efficiency in the regime of single and multiple charge state beam acceleration.

Table 1. Accelerating elements of the RIB linac.

Section	Geometrical beta, β_G	**Maximum A/q**	Frequency (MHz)	Number of Elements	Section Voltage (MV)
RFQ	-	240	12.125	1	1.23
H-RFQ-1	-	240	12.125	1	3.16
H-RFQ-2	-	66	24.25	1	2.86
SC	0.015	66	48.5	14	11.2
SC	0.025	66	48.5	24	30.5
SC	0.037	66	72.75	16	20.3
SC	0.037	15/2	72.75	6	6.5
SC	0.06	15/2	97.0	12	9.4
SC	0.105	15/2	97.0	36	38.3

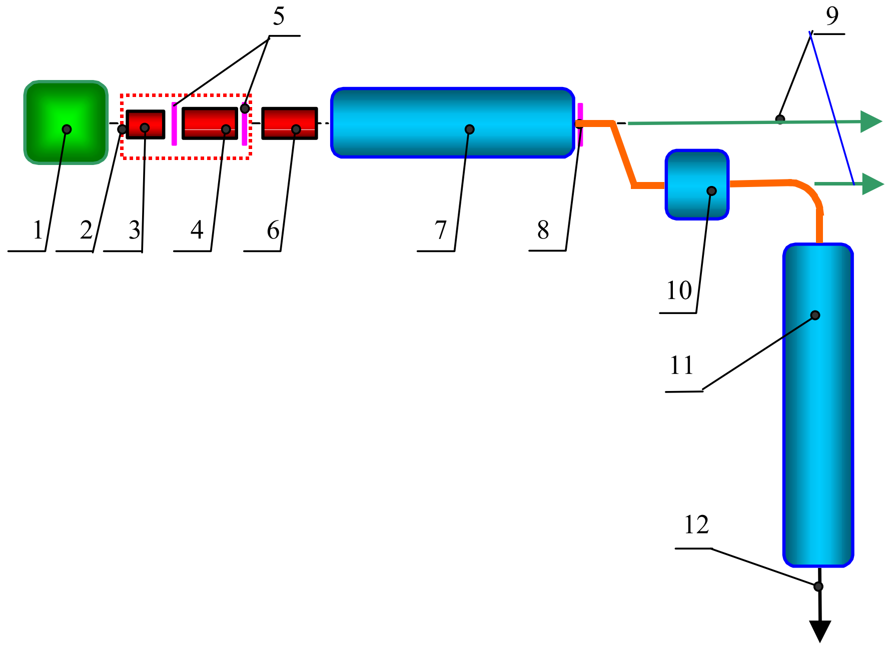

Figure 1.

Dual-potential mass separator

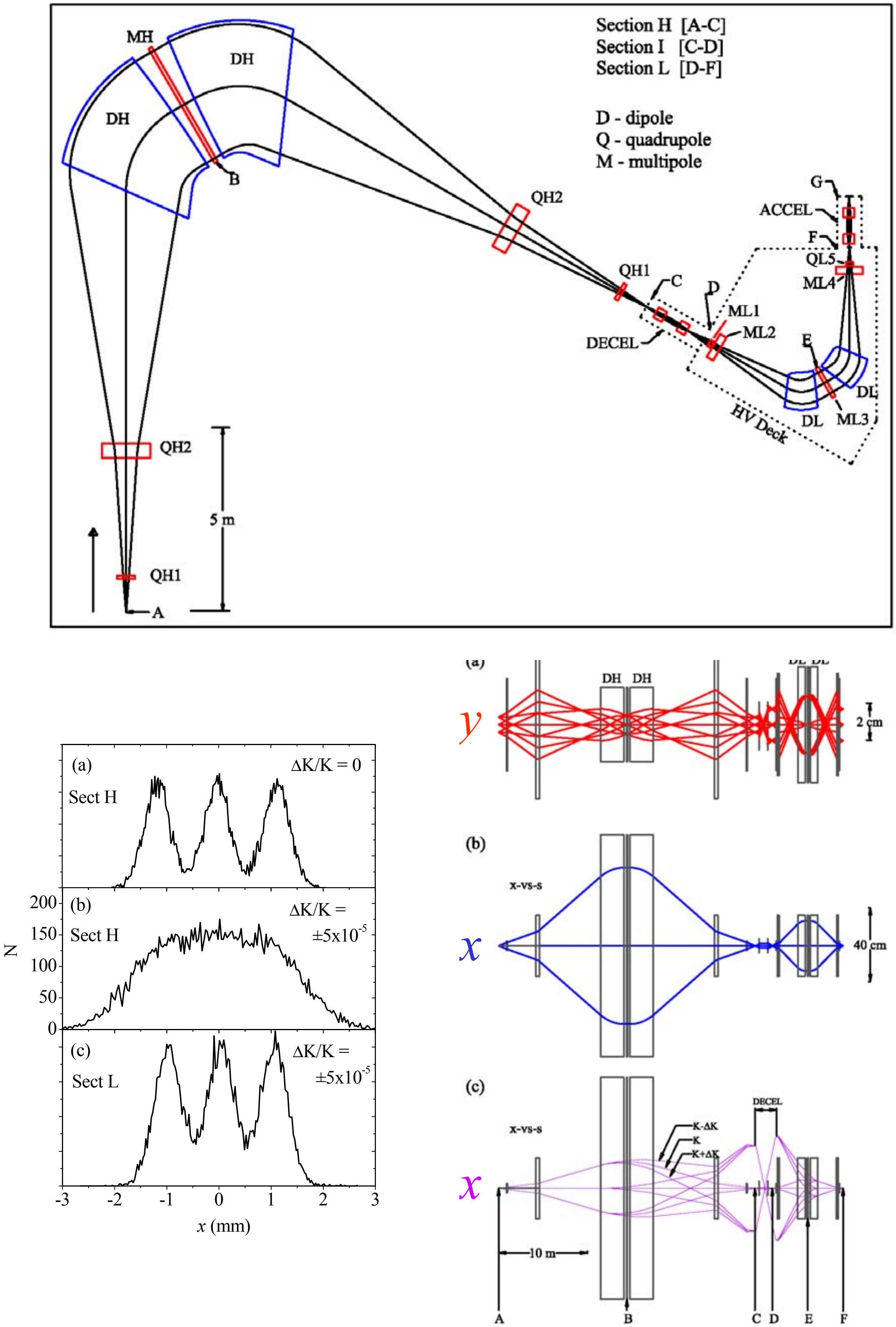

Figure 2

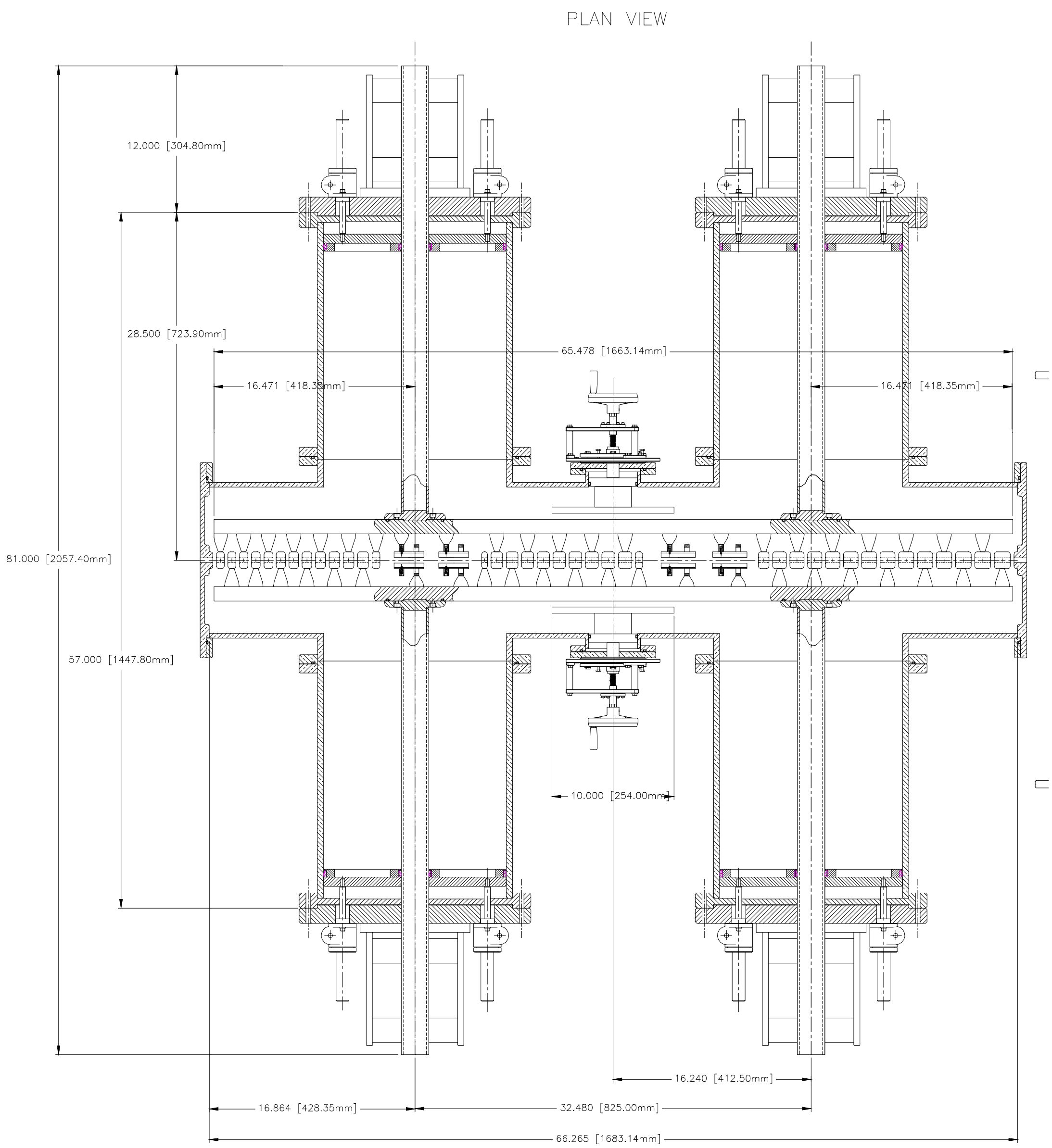
PLAN VIEW
12.000 [304.80mm]
28.500 [723.90mm]
65.478 [1663.14mm]
16.471 [418.35mm]
16.471 [418.35mm]
81.000 [2057.40mm]
57.000 [1447.80mm]
10.000 [254.00mm]
16.240 [412.50mm]
16.864 [428.35mm]
32.480 [825.00mm]
66.265 [1683.14mm]

Figure 3.

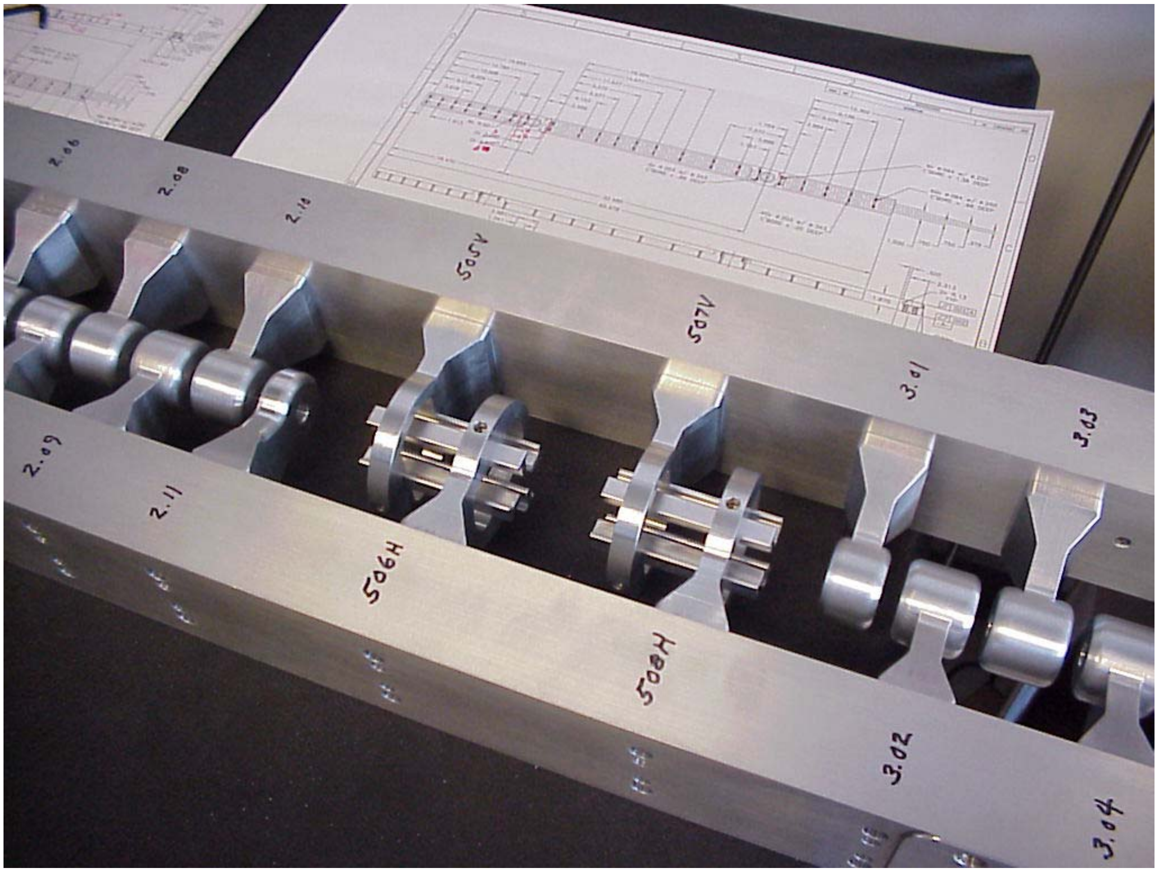

Figure 4.

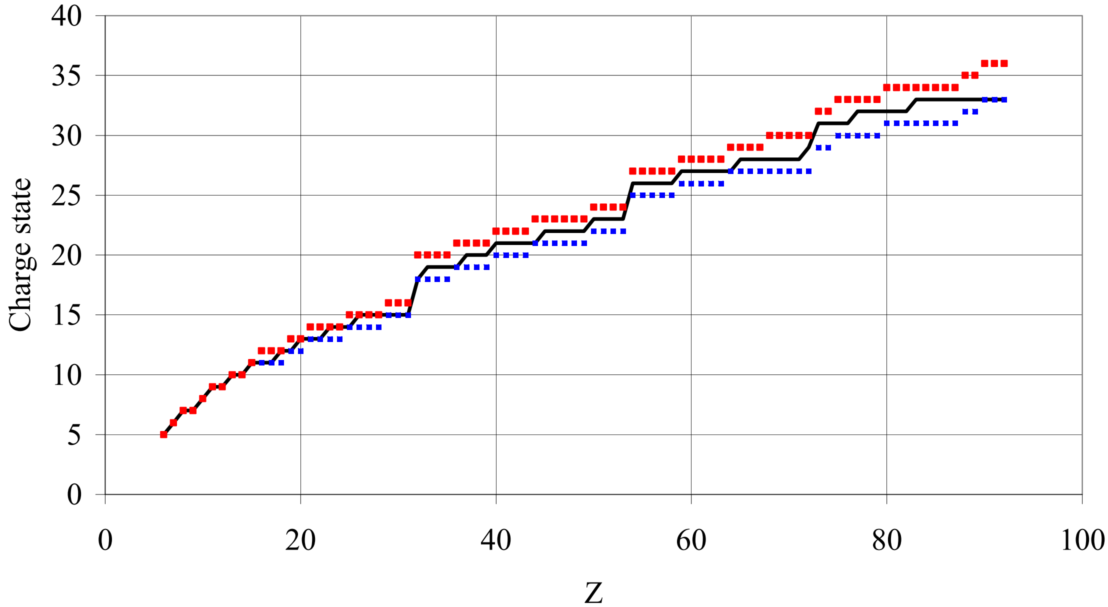

Figure 5.

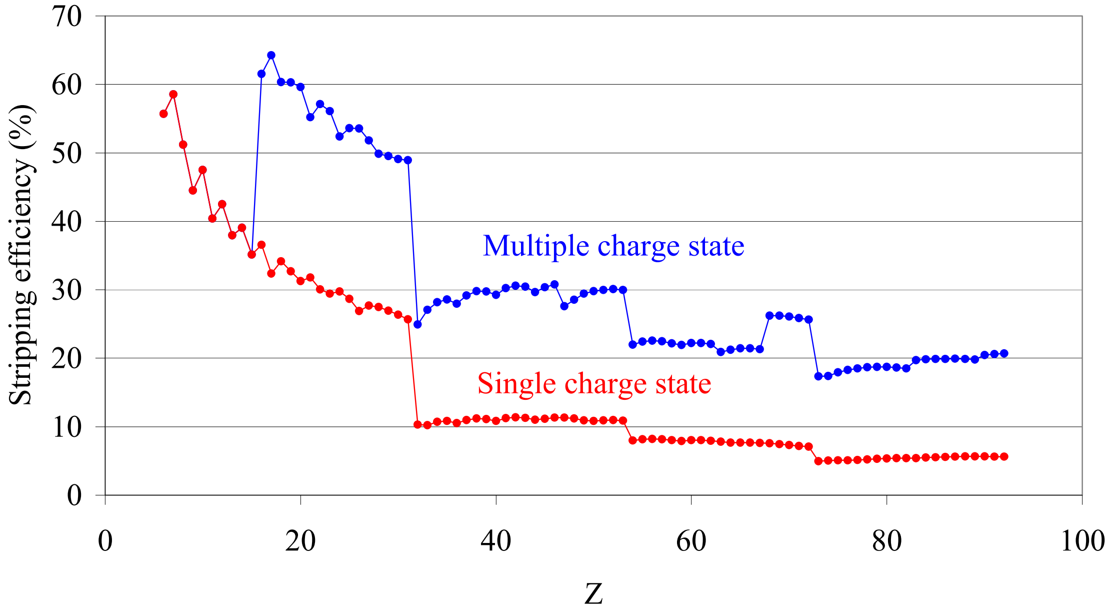
70
60
50
40
30
20
10
0
Stripping efficiency (%)
Multiple charge state
Single charge state
0
20
40
60
80
100
Z

Figure 6.